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ALKALI METAL THERMAL TO ELECTRIC CONVERSION RESEARCH

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Final Report

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14. Abstract The Phillips Lab and Alkali Metal Thermal to Electric Conversion (AMTEC) work focuses on three key issues: performance, lifetime, and durability. Lifetime includes demonstration of life operations and life limiting mechanisms. This report describes work aimed at improving cell performance through several generations of AMTEC cells. Practical application of this concept gives rise to a number of problems as revealed by the Phillips Lab experiments. Durability issues include demonstrating the ability of the cell to survive launch loads, shocks, and thermal cycles as well as developing more durable variants of the basic technology. To create the launch environments for these test requirements, a shaker table was procured and configured at Phillips Lab.

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LIST OF SYMBOLS

AMPS	Advanced Modular Power Systems
AMTEC	Alkali Metal Thermal to Electric Conversion
Cu	Copper
DAS	Data Acquisition System
GaAs	Gallium Arsenide
HCI	Hydrochloric Acid
Mo	Molybdenum
Na	Sodium
NaS	Sodium Sulfur
PL	Phillips Laboratory
Si	Silicon
TC	Thermocouple
TiN	Titanium Nitride
W/Rh	Rhodium

AMTEC PERFORMANCE EVALUATION TEST PROGRAM

1. INTRODUCTION

1.1 BACKGROUND

The Phillips Laboratory Power and Thermal Management Division (PL/VTP) is currently investigating of new methods and technologies for advanced space power concepts. As part of this research, PL/VTPN, in conjunction with ORION International Technologies, Inc. (ORION) is assessing various types of thermal to electric converters. The experiments conducted in this program were on Alkali Metal Thermal to Electric Conversion (AMTEC) devices. These devices incorporate a single beta"-alumina solid electrolyte (BASE) tube, however, a current generation of devices uses multiple tubes. These device are manufactured by Advanced Modular Power Systems (AMPS) and have the potential of providing all the benefits of static energy conversion at high efficiency, with a power output range from a few watts to megawatts.

1.2 DESCRIPTION

The AMTEC is a thermally regenerative electrochemical cell in which hot liquid Na is brought into contact with a preferentially conductive beta"-alumina solid electrolyte (BASE) barrier, which conducts Na^+ ions, but not atomic Na nor electrons. Electrons are drawn off through an external load and recombined with the Na^+ at a porous electrode on the low pressure side of the BASE. The neutralized Na atoms evaporate from the BASE, transit a vapor space, and condense on a radiator or condensing structure.. The condenser wick collects the Na liquid and pumps it back to the heat source and the hot liquid reservoir to complete the thermodynamic cycle. The Sodium-Sulfur (NaS) battery differs from AMTEC only in that an electrochemical potential is the driving force pushing the Na^+ through the BASE, rather than a thermodynamic potential as in the AMTEC. Figure 1 is a rudimentary schematic of the operation of an AMTEC cell.

1.3 PURPOSE

The PL/VTPN AMTEC work focuses on three key issues: performance, lifetime, and durability. Lifetime includes demonstration of life operations and life limiting mechanisms. This report describes work aimed at improving cell performance through several generations of AMTEC cells. Practical application of this concept gives rise to a number of problems as revealed by the PL experiments. Durability issues include demonstrating the ability of the cell to survive launch loads, shocks, and thermal cycles as well as developing more durable variants of the basic technology. To create the launch environments for these test requirements, a shaker table was procured and configured at PL.

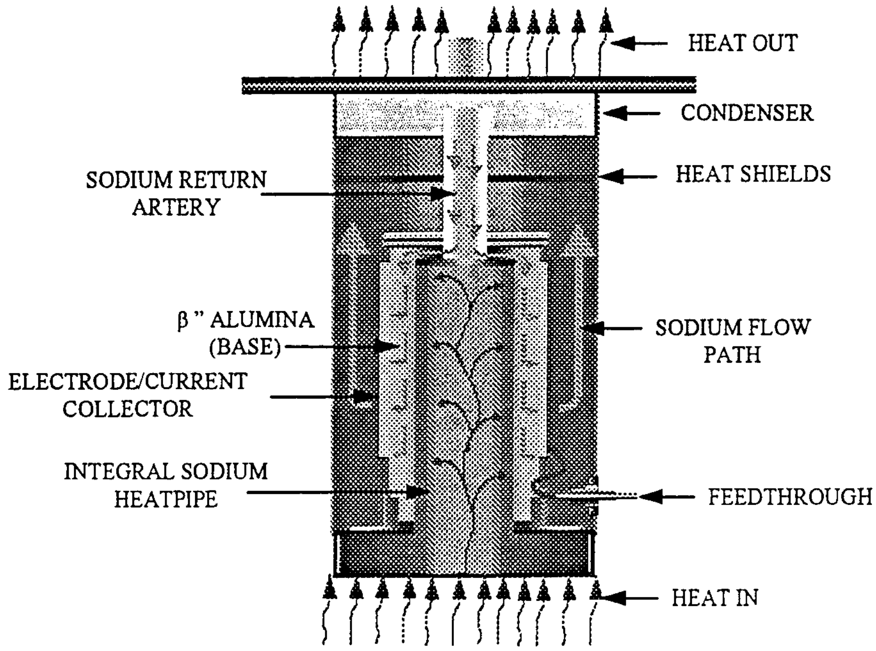

Figure 1. AMTEC Operational Schematic.

Directly condensed AMTEC cells with electromagnetic pump liquid return have operated for up to 14,000 hours (Ref. 1) Wick liquid return cells have operated in +/- 1-g conditions for as long as 11,000 hours (Ref. 1) Work done to date has found no problems that would prevent cells from running for 10 years or more.

For research cells not designed for high efficiency, typical efficiencies are in the range of 4 -12%.(Ref. 1 and Ref. 2). The highest efficiency cell operated at 19% (Ref. 3). In comparison, typical beginning of life efficiencies for photovoltaics are 14% and 18% for Si and GaAs solar cells, respectively. Predicted efficiencies for fully developed AMTEC cells are 25% for "typical" reactor temperatures (1300/800 K), 30% for "typical" solar thermal temperatures (1000/500 K), and 35% for radioisotope temperatures (1300/600 K). Predicted system specific power is significantly better than for competing systems at most power levels (Ref. 2).

Past wick return devices such as WR-4 and the Protosystem cells, have been constructed such that the Na condenser region of the cell is also indirect thermal contact with the hottest regions in the device. It is useful, therefore, to explore designs which allow the sodium vapor leaving the exterior of the BASE to condense in a location which allows the sodium to be cooler and wicking structure more efficient at circulating the molten Na. The concept of remote condensing is simple: remove the cold condenser region from direct radiative contact with the hot electrode surface to reduce parasitic heat losses. Results from tests of both wick return cells (WR-4, P-1 - P-6) and a remotely condensed cell (RC-10) are presented in this report.

2. WR-4

2.1 DESCRIPTION

The WR-4 series of AMTEC cells were designed for a nominal output power rating of 2 W at an operating temperature of 870 K with a maximum power output of 3.2 W at a BASE tube temperature of approximately 930 K (Ref. 4). Figure 2 shows the internal layout of the WR-4 AMTEC cell.

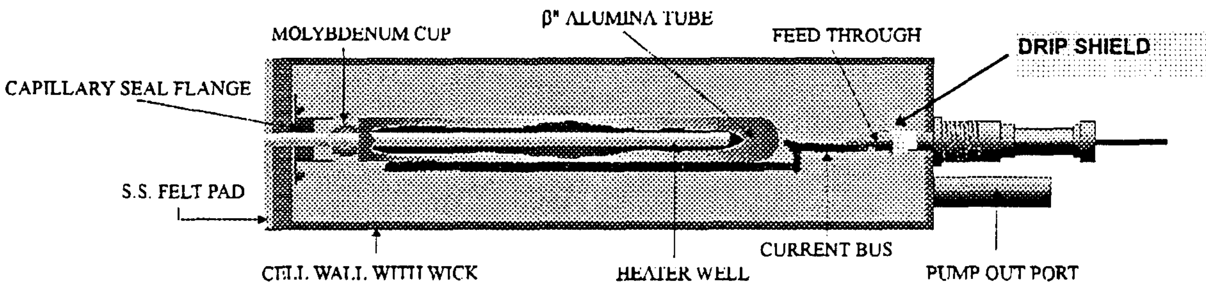

Figure 2. AMTEC Test Configuration.

The cell, fabricated from 300 series stainless steel, is evacuated to 10^{-6} Torr and baked to 570 K prior to being loaded with sodium. The positive electrical output feedthrough is relatively rugged, yet is too large to permit optimum efficiency for a device of this output capacity (Ref. 4). A drip shield was installed to prevent cold sodium droplets from dropping onto the hot BASE tube. The condenser shell (negative lead) provided the return path for the cell current flow.

2.1.1 WR-4 TEST CONFIGURATION

Six K-type thermocouples were mounted on the cell surface to monitor the external temperature and heat distribution profiles. The instrumentation and control for the cell operation (Figure 3) provided panel meter readings and temperature controls for heating the cell to operational temperatures. The temperature controller, in a closed loop configuration, provided power to the heater based on heater temperature limits which are programmed into the unit and monitored through a thermocouple placed on the heater. Power is applied to the heater as needed to maintain the temperature setpoint. An automated data acquisition system (DAS) was used in the test configuration for continuous monitoring and data collection.

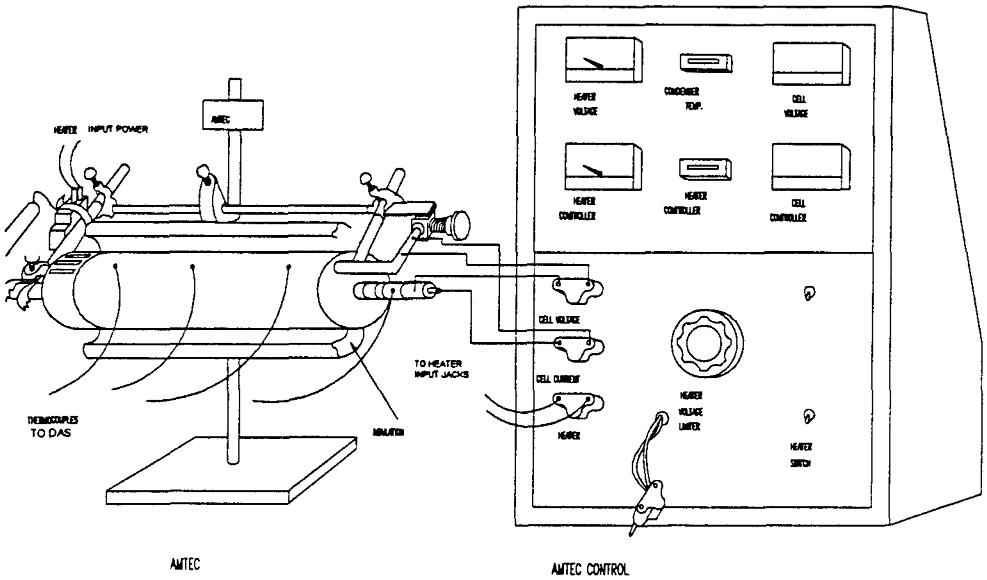

Figure 3. AMTEC Test Configuration.

2.1.2 WR-4 TEST PROCEDURES

Key operational constraints used for WR-4 cell included: a) limiting the ramp rate to less than 5 K/minute while the cell was unloaded and, b) never loading cell until temperatures exceed 390 K everywhere in the cell.

During initial runs at AMPS, the cell was operated in a variety of orientations for approximately 2,800 hours. A sample of the data collected is shown in Figure 4.

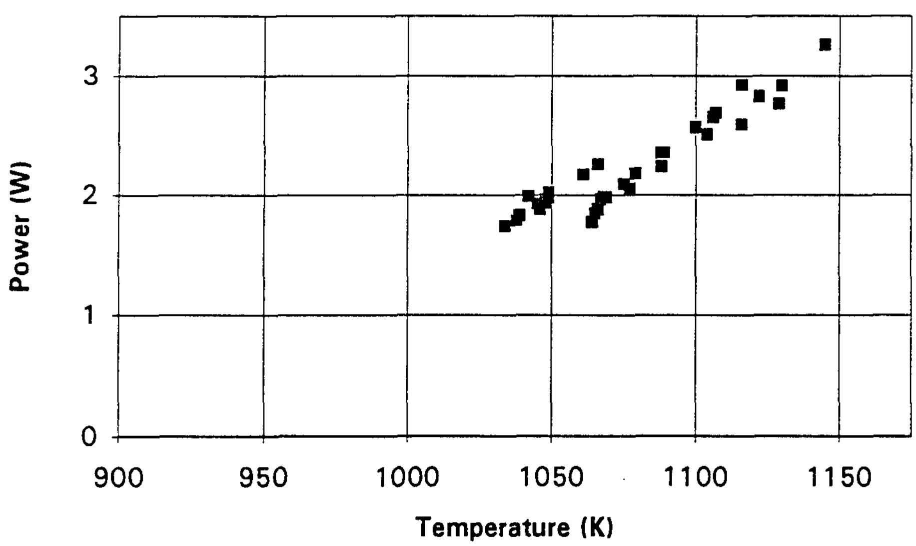

Figure 4. WR-4 Data (ERIM).

Initial runs at PL never produced comparable data to that obtained by AMPS even at heater temperatures exceeding 1200 K. During normal operations, the data collected at PL was approximately 30-40 percent lower than that reported by AMPS. Heater temperatures were increased in attempts to achieve similar data. As shown in the data, despite increasing the power output, the AMPS levels could not be achieved.

Another problem encountered during the PL tests was that the power output would vary significantly depending on where the negative power lead was placed. As shown in Figure 5, the data between 1050 K and 1200 K indicates data in which the negative lead was either placed at the bottom of the condenser (near the heater well) or on the pump out port (near the positive feedthrough). The higher power data points presented in that temperature range resulted when the negative power lead was placed at the condenser end of the cell.

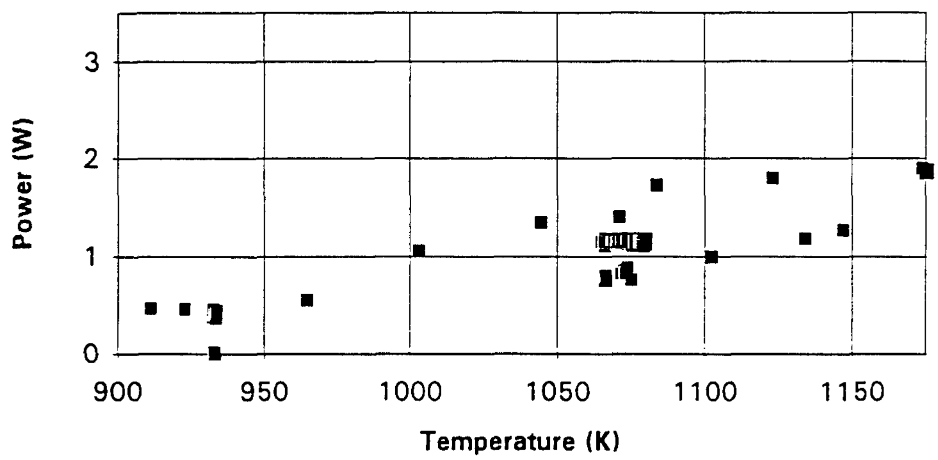

Figure 5. WR-4 Data (PL).

The procedures and configurations were reviewed to determine if any errors in the setup or operation had occurred. The heater temperature was reduced from 1200 K to 930 K to provide a baseline comparison temperature for the data collected at PL to the data collected at AMPS. However, shortly after reducing the heater temperature, the cell experienced a short (the voltage and current reduced to zero) while the heater remained at 930 K. The load was immediately removed from the cell and power was shut down to the system.

Review of the test conditions and consultations with the manufacturer resulted in several conclusions. First, reducing the heater temperature to 930 K was a problem, since this temperature was the lower limit for the BASE tube to operate under load, not the heater temperature specification. The heater temperature should have remained at 1100-1200 K. Secondly, the configuration of the cell heater produced cooler temperatures near the feedthrough than at the condenser end. The sodium to migrated to the colder region and created a buildup of sodium near the feedthrough which eventually caused a sodium bridge from the feedthrough (positive) to the cell exterior (negative) to form, shorting the cell.

The cell was re-configured to heat the feedthrough section of the cell and cool the condenser end in an attempt to condense the sodium at the feedthrough and freeze it into the condenser region. Special care was taken to keep the ceramic-to-metal seal (at the feedthrough) below 500 K to avoid damage to the seal.

Several alternative configurations (varying temperature and insulations) were attempted with varying cell orientations to accomplish the above. However, changes were not noted in the cell performance in any configuration. The next planned step was to drill small holes into the cell to allow viewing of the internal components (while inducing minimal damage to the cell). To perform this procedure, the cell was placed in a glovebox and holes were drilled for borescope penetration to view the internal components. Upon initial inspection, a sodium buildup was identified at the dripshield/feedthrough and pumpout port as shown in Figure 6. The buildup of sodium at the pumpout port precluded re-evacuation of the cell unless the port was cleared. Because of problems encountered with the glovebox, much of the sodium was oxidized, thus requiring scraping of the residual sodium in the port, both internally and externally. After clearing the port, the cell was resealed, re-evacuated and once again re-heating procedures were attempted. Summary results are presented in Section 3.1.

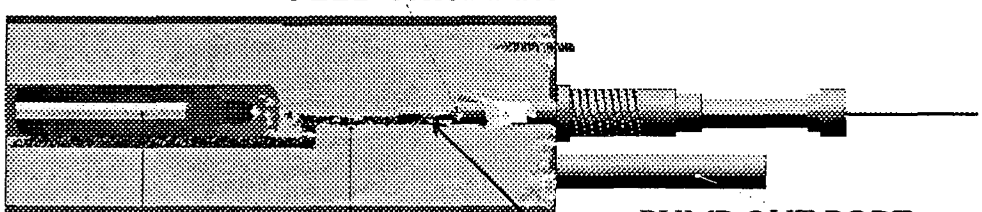

Figure 6. WR-4 Showing Sodium Deposits.

2.2 SUMMARY RESULTS AND CONCLUSIONS

2.2.1 WR-4 SUMMARY

Through the process of cell operation and dissection, ORION and PL were able to determine operating parameters and failure points of the WR-4 series. This information has been used to progress the development of AMTEC cells as described in the follow-on tests described in this document.

2.2.2 WR-4 RESULTS

After removal of sodium from the dripshield/feedthrough by way of the bore holes, a second series of re-heat procedures failed. Therefore, the cell was cut open (Figure 7) and inspected. A short had been created because a large amount of sodium had collected *under* the drip shield and a sodium bridge had formed from the drip shield to the feedthrough. The oxidized sodium had coated the clean sodium, providing an insulating barrier, which prevented the removal of the sodium through re-heating procedures. Much higher temperatures were needed to melt the oxidized sodium; such temperatures would have melted the feedthrough braze, ruining the cell.

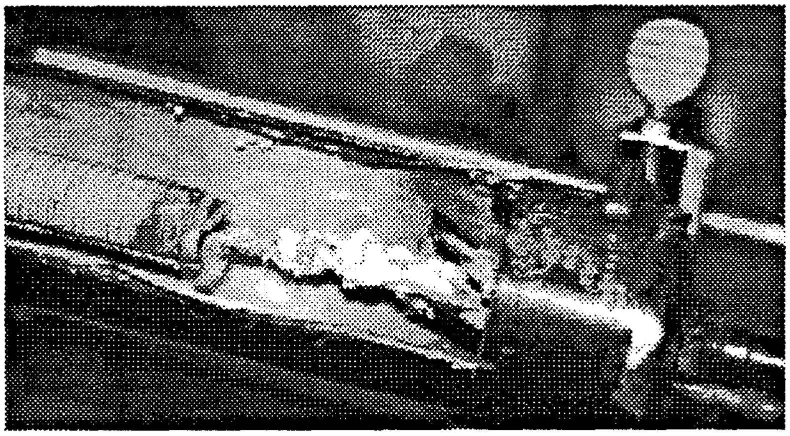

Figure 7. AMTEC Dissection Showing Sodium Collected Under Dripshield.

The cell was thoroughly cleaned with diluted hydrochloric acid (HCl), dried in a vacuum chamber and configured for vibration testing. During an 8 -g random vibration test (it survived 4g rms), the BASE tube separated from the metal support ring on the cell. As shown in Figure 8, the BETA tube was partially fractured, and eventually experienced complete separation at the braze point.

SEPARATION POINT

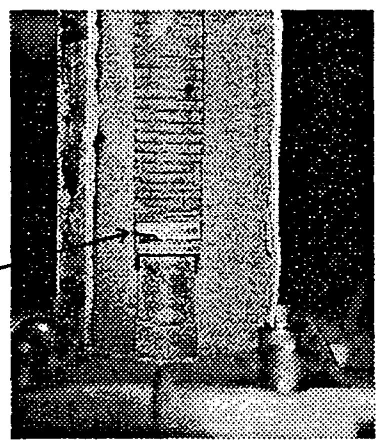

Figure 8. BETA Tube Separation, 8g rms Vibration Test.

2.2.3 WR-4 CONCLUSIONS

Several conclusions can be made from the inspection of the AMTEC cell. First, a potential problem exists with the AMTEC the braze point of the BASE tube to the metal support ring. While this is one of two known cells to have experienced this problem, these cells have also undergone additional stresses of shipping after laboratory tests have been performed at the manufacturer facilities.

The second conclusion is that the larger feedthroughs act as a heat sink to the cell and thus cool the "hot" section of the cell. As shown from our results, this creates a sodium buildup at the feedthrough. These data have proven beneficial, since this problem with sodium inventory was encountered in the RC-10 tests conducted at PL as well. A sodium inventory problem was suspected for this test, since the voltage and current indicated zero readings. While the construction of the RC-10 cells was different than WR-4, the symptoms were similar as indicated in Section 3.2.

Third, the optimum negative feedthrough should be identified for each cell. The power output performance changed significantly as the location of the negative lead was varied.

Finally, while the drip shield may be necessary to protect the BASE tube, a redesign should be considered. The outside diameter of the shield and the cell exterior are in close proximity and create a potential gap for sodium buildup, and eventual shorting. Design changes have resulted and the newest generation of AMTEC devices allow sodium to condense in a region which is no longer located near the heater input region, eliminating areas in which sodium can condense unintended and eliminating the drip shield.

3. RC-10

3.1 DESCRIPTION

Figure 9 shows the internal layout of the RC-10 cell. Several significant features should be noted. First, the hot BASE tube is thermally isolated from the colder parts of the cell, both by radiation shields and by a long transition piece. The reason for this isolation is to reduce the amount of heat input required to keep the BASE tube at any given temperature. Second, the positive feedthrough metal to ceramic seal is thermally isolated from the rest of the cell by a very long transition piece. The reason for this isolation is to keep the temperature of the metal-to-ceramic seal as low as practical to preserve the vacuum integrity of the cell. Third, the only wicked portion of the cell is at the condenser; it is connected to the evaporator region by an annular arterial wick. Fourth, most of the cell wall is covered by the guard heater assembly (as shown in Figure 10) to reduce heat losses and allow us to control the cell wall temperature profile. Overall dimensions of the cell, not including feedthrough, are 29.5 cm long by 3.2 cm diameter. The BASE tube is 10.9 cm long by 1.5 cm diameter. The electrode area is 47 cm^2.

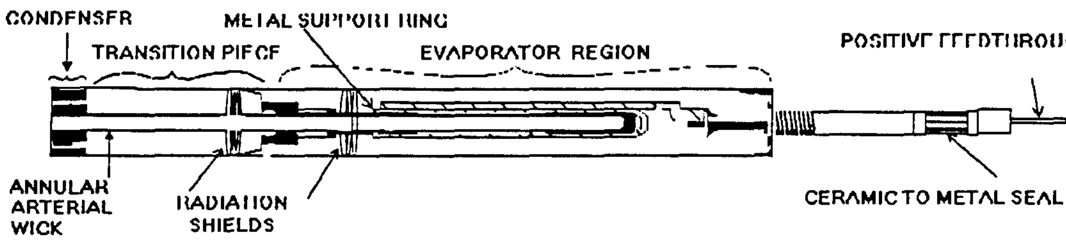

Figure 9. AMTEC RC-10 Cell.

The guard heater consists of an insulation shell and three ceramic-imbedded furnace heater elements, each controlled by separate controllers and variable transformers. The guard heater is used to maintain adiabatic temperature conditions on the cell wall, there by retarding heat loss, or to otherwise control the exterior temperature profile of the RC-10 to the effects of cell wall temperature variations on efficiency. In addition, the guard heater may also be considered to simulate the presence of other surrounding systemic heat sources.

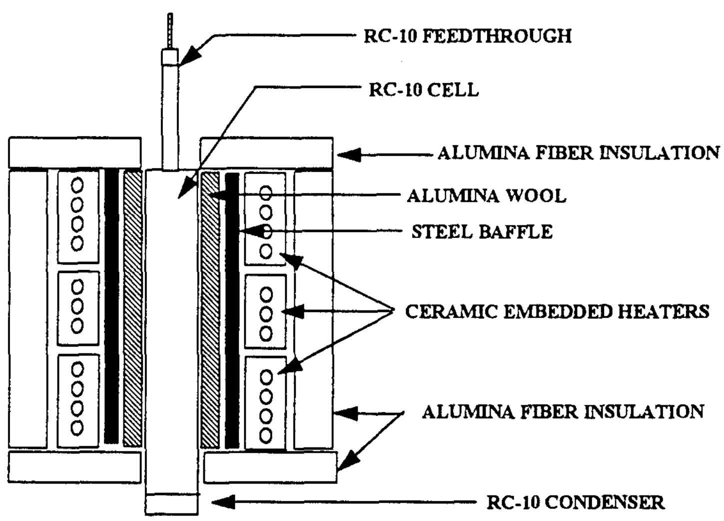

Figure 10. Guard Heater Assembly.

3.1.1 RC-10 TEST CONFIGURATION

The purpose of these tests were to determine the functional characteristics and operational life expectancy of the AMTEC RC-10 device. The cell was placed vertically on the test stand, with the guard heater installed along the cell length. The entire apparatus fit easily into a standard six-foot rack.

During normal, long-life, operation, the BASE tube was kept within a nominal temperature range of approximately 913 K to 933 K. The BASE tube temperature could not physically be measured, however, calculations indicate a cartridge heater temperature of 1073 K would produce the appropriate BASE tube temperature. The cartridge heater was recorded throughout the test.

The RC-10 cell was not intended to be operated in any orientation other than vertical. No plan for operating the cell in other orientations was included in the test procedures although the support hardware and rack allowed for the cell to be angled as much as 30°.

3.1.1.1 RC-10 THERMAL PROFILING

The RC-10 was thermally mapped using thermocouple probes which were placed along the length of the cell exterior and also along the length of the guard heater inside of a 1 mm bore stainless tube. As mentioned previously, the intent of the guard heaters were to maintain adiabatic temperature conditions on the exterior of the cell and to induce changes in the exterior profile of the cell. Thermal mapping was performed on the cell and guard heaters with and without the guard heaters in operation.

3.1.1.2 RC-10 DATA ACQUISITION AND INSTRUMENTATION

All of the testing performed on the cell took place in the test rack shown in Figure 11. The cell and its associated guard heater assembly were held by band clamps attached to metal rods; this arrangement provided thermal and electrical isolation for the cell. The test rack instrument layout allowed the experimenter to see all of the important operating parameters at a glance.

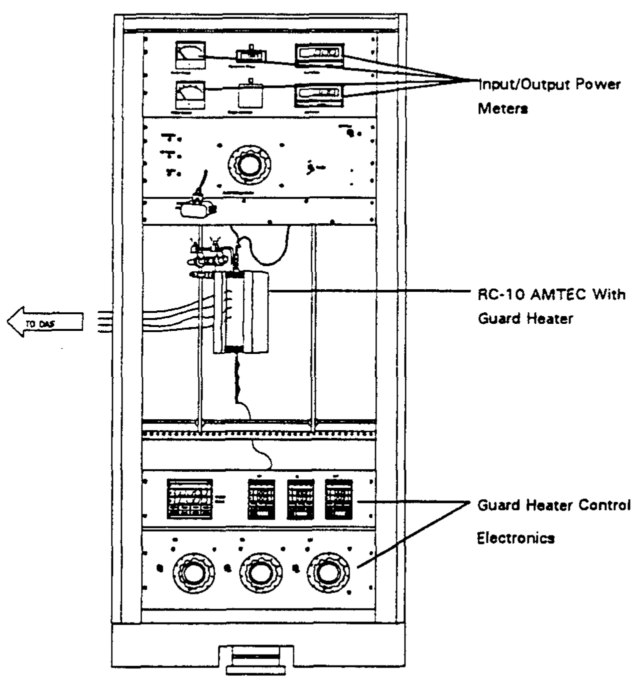

Figure 11. RC-10 AMTEC Test Configuration.

Data collected included temperatures, output current and voltage, and input power. K-Type (chromel-alumel) thermocouples were used for all temperature measurements. Output current and voltage were measured using voltmeters; the current was calculated using the measured voltage drop across a one milliohm resistor. Input power was measured by first adjusting the input heater power rheostat to give steady temperatures and then reading input voltage and current.

Initial data was taken using the panel meters available on the AMTEC control panel. This data was logged periodically into the experiment record log and transferred into a spreadsheet for future review and analysis. The second phase of testing was used to validate an automated DAS using a 486-25 MHz computer with data acquisition and multiplexing cards. The cards contained reference junctions for the K-type thermocouple interface and signal conditioning capabilities for low level signals. The DAS recorded voltage and temperature measurements as well as provide I-V plots for data analysis. The system was configured with an initial sampling rate of 0.1 Hz.

3.1.1.3 RC-10 DATA REDUCTION AND ANALYSIS

Preliminary test data was logged in conjunction with data acquired by the DAS. This provided baseline data for comparison to data obtained by the DAS. The DAS provided data files for each set of data taken. A software routine was implemented to update the data file name each time a new set of data is recorded. Files with varying sample frequencies were merged to provide one data file per test sequence. The data was continuously recorded on the hard-drive. Periodically, the data files were saved on 3 1/2-inch disks for storage and transfer. The data was recorded in engineering units and did not require pre-processing prior to review or analysis.

3.1.1.4 RC-10 INSTRUMENTATION

The RC-10 AMTEC cell was configured with five K-type thermocouples (TCs) distributed along the length of the cell as shown in Figure 12. Thermocouples were attached to the bottom of the cell and at the junction of the feedthrough to the main body of the cell. The TCs were all secured using a high temperature thermal compound. The guard heater was with three thermocouples so that the heaters could be controlled with heater controllers. Another thermocouple was inserted into a small stainless steel tube attached to the baffle in the guard heater and could measure the temperature at any location along the axis of the guard heater. An internal thermocouple on the cartridge heater, supplied by the manufacturer, was used to control the cartridge heater temperature. All thermocouple outputs were recorded by the DAS.

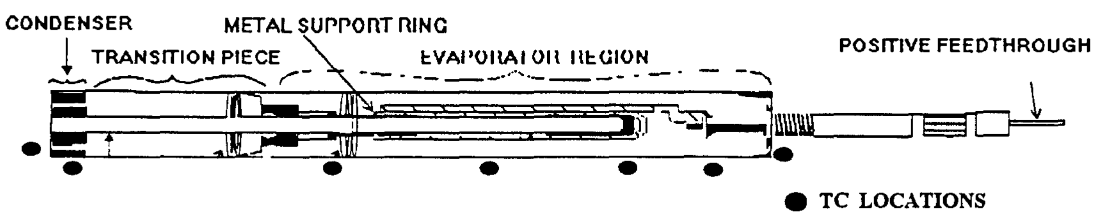

Figure 12. AMTEC Cell Thermocouple Test Configuration.

The AMTEC voltage and current output were monitored using panel meters and the quick view functions on the DAS. The voltage drop across a series 1-milliohm resistor was used to measure the current output. To determine the current-voltage relation, a regulated DC power supply was connected in series with the cell as shown in Figure 13. The voltage on the power supply was limited to 1 V to avoid overdrive and short circuit conditions if the cell voltage was accidentally reversed. The cartridge heater used AC power and the DAS was able to record input and output powers.

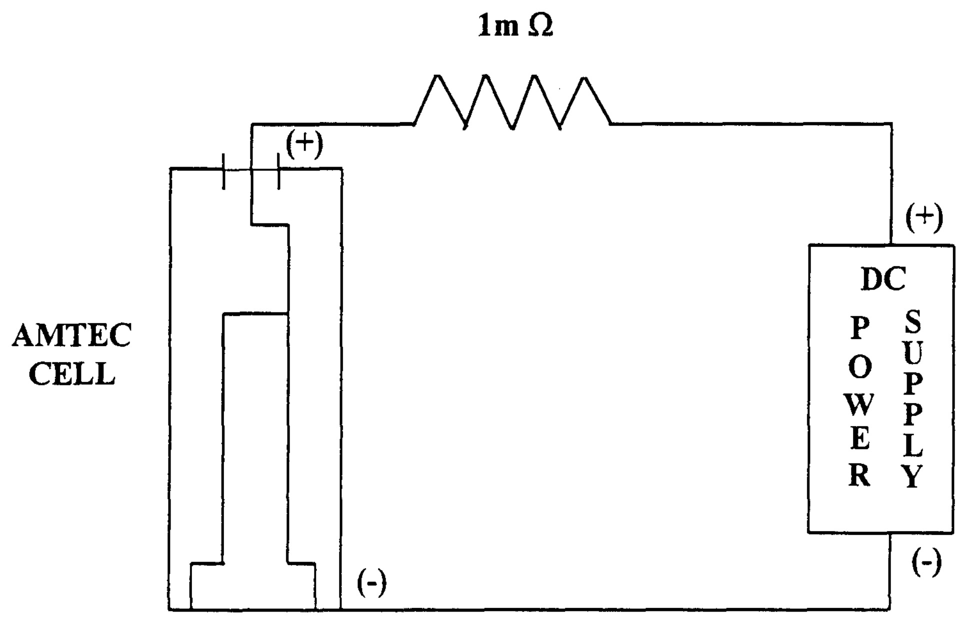

Figure 13. AMTEC Load Circuit.

3.1.2 RC-10 TEST PROCEDURES

Most of the cell handling procedures were provided by the manufacturer, AMPS. Key operational constraints used for RC-10 include: a) limiting the ramp rate to less than 5 K/minute while the cell is unloaded; b) never loading cell until temperatures exceed 393 K (freezing point of sodium) everywhere in the cell. Table 1 provides the procedures used to start and operate the cell.

Table 1. Start-up and Shut-down Procedures.

	START-UP PROCEDURES	
1	Power is supplied to rack by a single switch	TURN ON RACK POWER
2	Power to cartridge heater is supplied by two switches	TURN ON BY-PASS
		TURN ON HEATER POWER
3	Current to heater is supplied by auto transformer (xfmr)	TURN XFMR TO 10%
4	Start data acquisition	RUN LABTECH NOTEBOOK
5	Initiate guard heater (GH) operation	TURN ON GH SWTCHES
	Allow at least 15 minutes before readjusting GH	TURN GH XFMRS TO 10%
6	Take temperature profile along GH and Cell	READ TC EVERY 1.5 CM
7	Heat cartridge heater to 873 K, if condenser is > 423 K load cell	PLUG CELL INTO LOAD
8	Increase heat to GH. Do not exceed cell wall	TURN UP GH XFMRS
	SHUT-DOWN PROCEDURES	
1	Unload cell	UNPLUG LOAD
2	Turn off power switches to GH, zero auto transformers	TURN OFF GH SWITCHES
		TURN XFMR TO 0%
3	Turn of power to cartridge heater and zero auto transformer	TURN OFF HEATER POWER
		TURN XFMR TO 0%
4	Turn off rack power	TURN OFF RACK POWER
	EMERGENCY SHUT-DOWN	
1	Turn off rack power	TURN OFF RACK POWER

3.2 SUMMARY, RESULTS AND CONCLUSIONS

3.2.1 RC-10 SUMMARY

In our initial experiments, we attempted to duplicate the qualification trials performed at AMPS. In general, these experiments did not match the results seen at AMPS, mainly because of initial problems in controlling the guard heater temperatures. PL's experimental setup also appears to have considerably higher line losses, thus causing lower apparent cell performance.

3.2.2 RC-10 RESULTS

In spite of the problems encountered duplicating manufacturer results, experiments successfully demonstrated the utility of remote condensing. This demonstration was accomplished by first heating the cell up using only the internal heater and then slowly increasing the temperature of the guard heaters (which in turn affects the cell wall temperatures). Figure 14 shows a plot of internal heater power input, cell power output, and cell efficiency as functions of peak guard heater temperature. The data points, up to a peak guard heater temperature of 953 K, were collected with the internal heater temperature set at 1023 K. At higher peak guard heater temperatures, the internal heater temperature was increased to 1073 K to insure that the BASE tube surface temperature exceeded the cell wall temperature. Efficiency increased substantially as the guard heater temperature was increased, going from 2.2% for a guard heater temperature of 653 K to 5.8% for a guard heater temperature of 953 K. The condenser temperature at this point was 481 K, compared to 565 K at a similar point in manufacturer trials. The temperature indicated that more heat was being lost by conduction. In addition to more closely approximate an adiabatic surface, the guard heater temperature was held closer to the cell wall temperature in tests conducted at AMPS than those in PL tests.

In operating the cell, Na inventory problems were encountered, characterized by sudden, drastic reductions in output current and voltage. These problems were caused by a combination of cell design and operation. Figure 15 shows a plot of the cell wall temperature distribution during initial operation (observe the curves peaking near 890K). The key aspect of this plot is the peak in the cell wall temperature. Sodium evaporating from the BASE tube "above" the peak will move down the temperature gradient to the top of the cell, where it condenses on the cell wall. It is then lost, because it has no return path (absence of a wick).

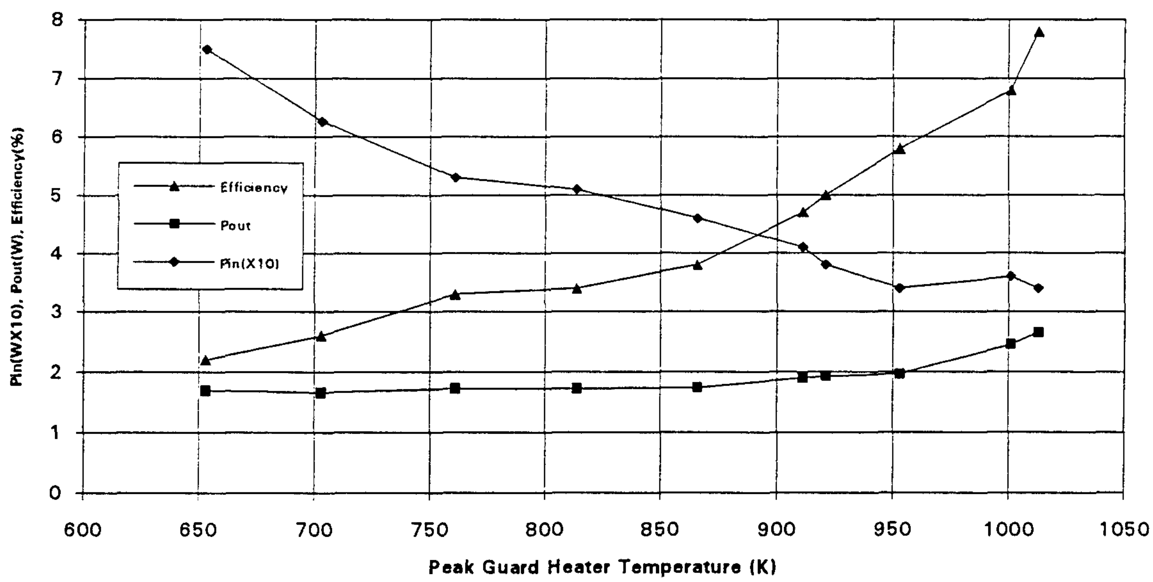

Figure 14. Power and Cell Efficiency of RC-10.

Experiments determined that the temperature distribution was creating a problem, thus corrective action was taken by altering the guard heater/cell wall temperature profiles, as shown in Figure 15 (topmost curves). When this action did not correct the problem, heater tape was wrapped around the feedthrough and pumpout port. The top guard heater was used to heat the top of the cell, while the bottom of the cell was cooled with a fan. The plan was to force the Na inventory to condense in the bottom of the cell to correct the distribution problem.

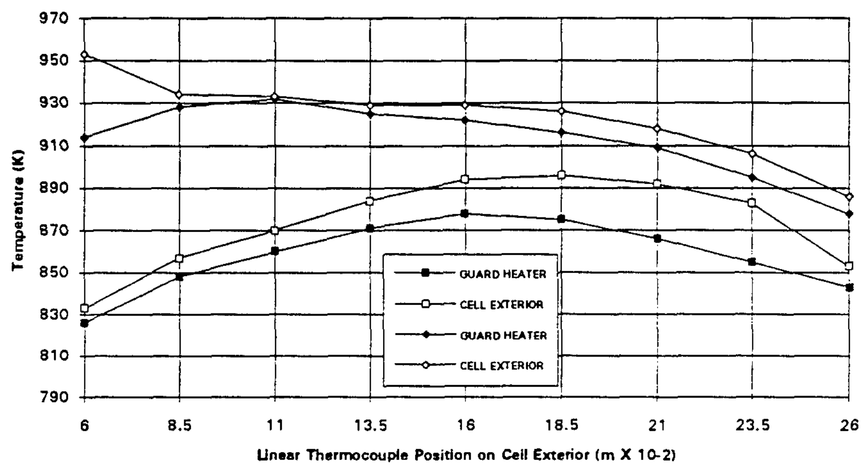

Figure 15. Plots of Cell Exterior and Guard Heater.

The heating efforts tended to degrade rather than improve the performance of the cell. The cell was then opened to inspect its internal components. The cause of the performance problems was apparently a complete separation of the BASE tube from its metal support ring. This separation appears to have occurred as a result of the failure of the ceramic to metal braze. It is likely that this separation did not occur at once, but gradually over time, and was responsible for most of the performance degradation problems seen. Visual inspection revealed 99% of the Na inventory was in the lower baffles and condenser wick, with only small patches left on the current bus. The heat distribution corrective actions apparently worked as expected and would have restored the cell's performance, were it not for the braze failure.

3.2.3 RC-10 CONCLUSIONS

The key conclusion from this work is that remote condensing does increase efficiency, but not power output. Again referring to Figure 14, note that the cell power output was nearly constant for a constant BASE tube temperature and peak guard heater temperatures from 653 K to 953 K. The slight increase in power output was probably due to a slight increase in BASE tube temperature over this range. This data indicated vacuum operation of AMTEC cells is feasible as the heat input required should be reduced without reducing the power output.

A second conclusion from this work is that the cell, when operated correctly, is capable of high efficiency. Most, if not all, of the performance problems seen were due to the separation of the BASE tube from its metal support. Consequently, recommendations were made for investigating brazing techniques and braze material limitations. It should be noted, however, that only two of the last 22 cells fabricated by AMPS in the last two years have failed because of a braze joint problems.

4. PROTOSYSTEM CELL TESTS

4.1 DESCRIPTION

The protosystem cells, tested by ORION for the PL/VTP, are constructed like the WR series of cells with only minor variations in the materials used as electrode materials and current collectors. In operation, heat is supplied to the BASE by a heat pipe constructed separately by Thermacore Inc., which is inserted into inconel heater well (Figure 16). The cells are geometrically identical, but have different electrode and current collector materials. Cells P-1 and P-2 (PL/VTP designations) have tungsten-rhodium (W/Rh) sputter deposited electrodes and molybdenum (Mo) current collectors. Cells P-3 and P-4 have titanium nitride (TiN) electro-deposited electrodes and Mo current collectors. Cells P-5 and P-6 have TiN electrodes and copper (Cu) current collectors. The odd numbered cells were constructed with a single thermocouple penetrating the shell of the device to collect data about the temperature of the BASE (Figure 16).

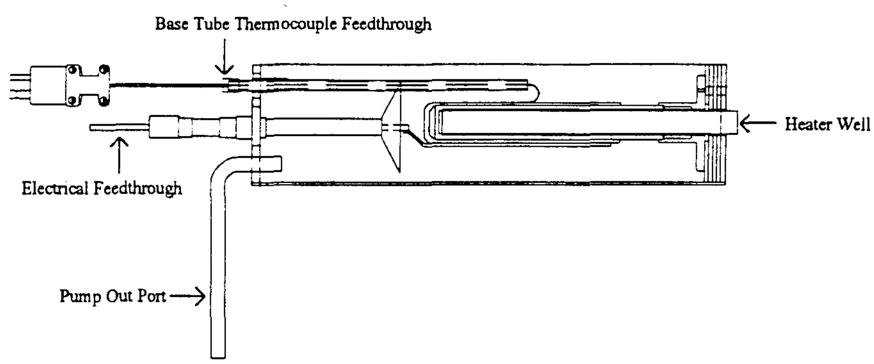

Figure 16. Protosystem Series Cell Showing BASE Thermocouple.

An important point concerning these cells is that they were not designed for high efficiency. Rather, they were designed for low cost production, to allow PL to purchase a large quantity with limited funds. The PL intended to push the cells' mechanical and electrical environments, looking for failure points.

4.1.1 PROTOSYSTEM TEST CONFIGURATION

The cell test setup for operation in air was configured as shown in Figure 17. From one to six of the cells could be mounted in the test rack. The cells were also oriented vertically in the vacuum test stand and tested individually. For air operation, cartridge heaters, constructed from alumina and Kanthal heater wire, were inserted into the heater wells of the devices. Specially designed heat pipes, built by Thermacore, Inc. (Figure 18), were designed and built to furnish heat to the cells when all six cells were operated in systematic fashion.

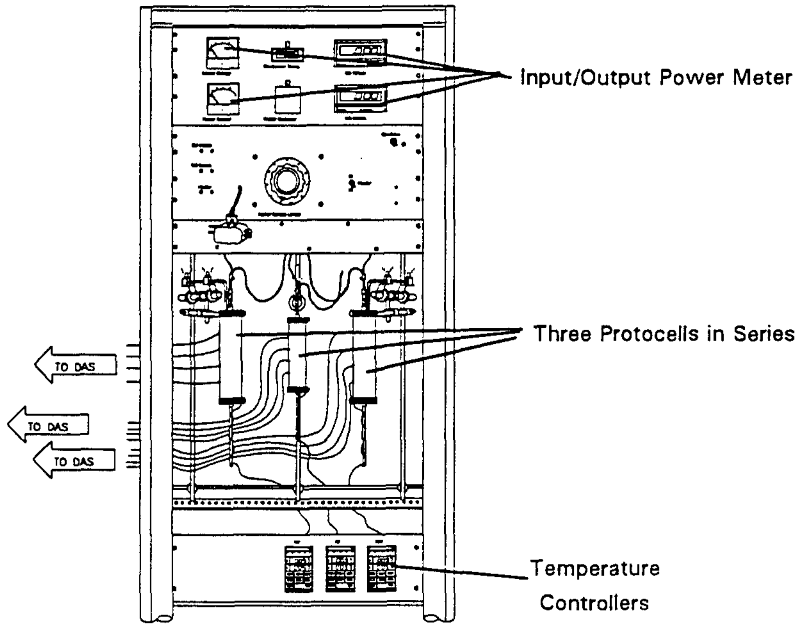

Figure 17. AMTEC Protosystem Test Configuration.

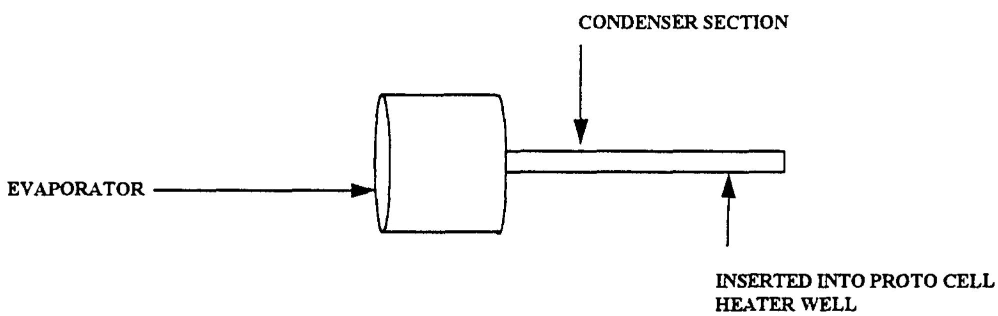

Figure 18. Thermacore Heat Pipe.

Each cell was characterized in air. The tests were performed to verify the performance the manufacturer-specified. Three of the cells were designed with a K-Type TC penetrating the interior of the cell and attached to the BASE tube. Data from these TCs is valuable in verifying calculations of the BASE temperature.

The cells were thermally profiled using K-Type TCs attached to the exterior of each. Five such TCs were cemented to the body of each of the cells, one was attached to each of the cell bottoms, and one TC was attached at each of the junctions of the feedthrough and cell body. Figure 19 is a map of the TC positions. Such information was valuable in observing heat loss mechanisms and their effects on the cells. During air operation, the cells were individually wrapped in alumina fiber insulative material.

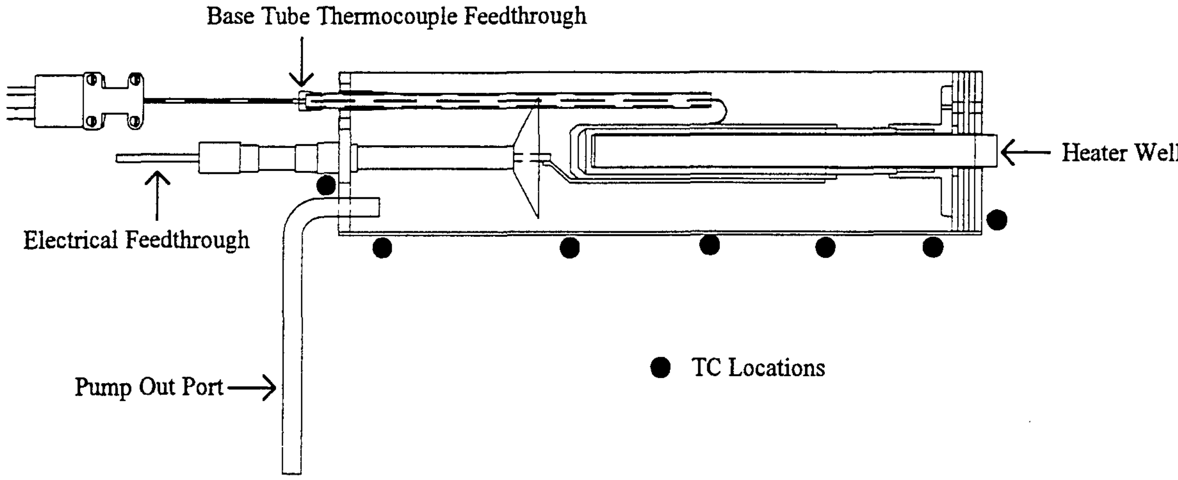

Figure 19. AMTEC Cell Thermocouple Test Configuration.

4.1.2 TEST PROCEDURES

During the testing, the BASE tubes were supposed to be tested at temperatures varying from 873 K to 973 K. The BASE tube temperature was intended to be measured directly on three of the cells because of the built-in thermocouples; a cartridge heater or heat pipe temperature of 873 K to 1073 K produced this range of BASE tube temperatures. The evaporator of the heat pipe had to be heated to between 1073 K and 1173 K to obtain a temperature of 1073 K at the condenser end which was inserted into the heater well. The heater and heat pipe temperatures were recorded throughout the tests.

Current versus voltage (I-V) data was taken while exercising the cell through its entire current-voltage range. To determine the current-voltage relation, a regulated DC power supply was connected in series with the cell (see Figure 20). Although cell efficiency is important, these cells were not designed for high efficiency; they are high power cells and the PL expected as much as 3 - 4 W power from each. The AMTEC voltage and current output were monitored using panel meters and a DAS. A 1-milliohm resistor is used to determine current output. The voltage on the power supply was limited to 1 V to avoid overdrive and short circuit conditions if the cell voltage was accidentally reversed. Both input and output power were recorded by the DAS.

Although these cells can be operated in almost any orientation, they were operated vertically so that close packing arrangements, within the confines of the rack and eventually the vacuum system, could be tested.

4.2 PROTOSYSTEM RESULTS

Each cell was tested in air, and current and voltage data was taken at a fixed load point (DC power supply not in circuit) for increasing temperature. This data was compared with the manufacturer's data. Figure 21 shows the heater temperature versus power output of all six cells. The data for the even numbered cells (those without a BASE tube TC) matched that taken by AMPS prior to the shipment of the cells. However, the cells instrumented with a BASE tube TC did not fare well in shipment. Two of the thermocouples broke off in shipment and as the data indicate, the devices did not perform to the manufacture's specifications.

The data also indicates that for temperatures above 1250 K the TiN electrode/Cu current collector materials produced higher output power because of lower $\in$. Below 1250 K heater temperature there is little difference, although the tungsten-rhodium electrode and molybdenum current collectors seem to have a slightly higher power production.

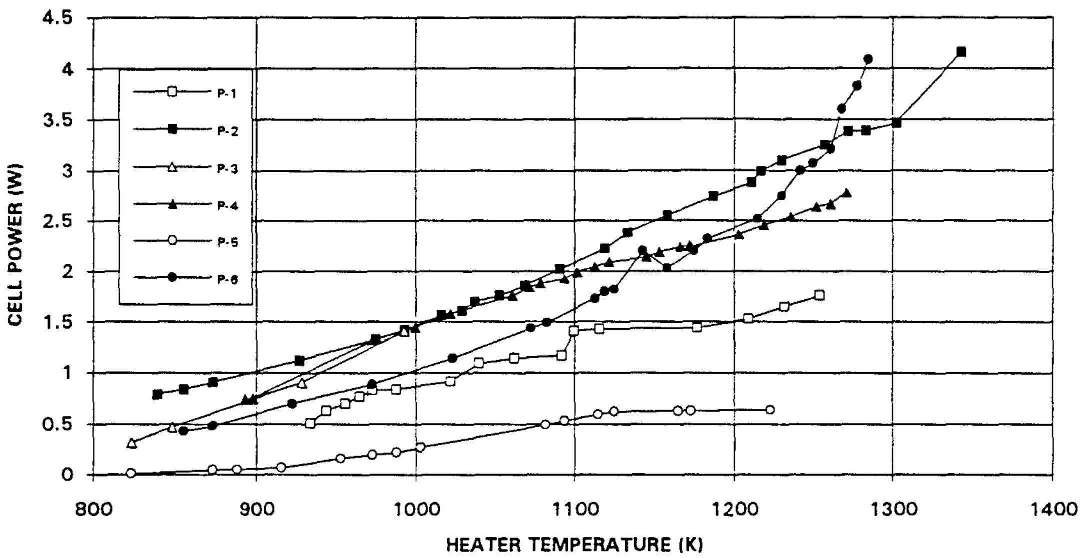

Figure 20. AMTEC Power Output Versus Heater Temperature at 1mΩ Load

Performance of the odd numbered cells continued to degrade and after several months sodium was observed to leak from the thermocouple feed through. The even numbered cells continued to function well and were used in a series circuit together. This test was performed in air and Figure 21 displays the resultant I-V curve with all three device heaters at 1100 K.

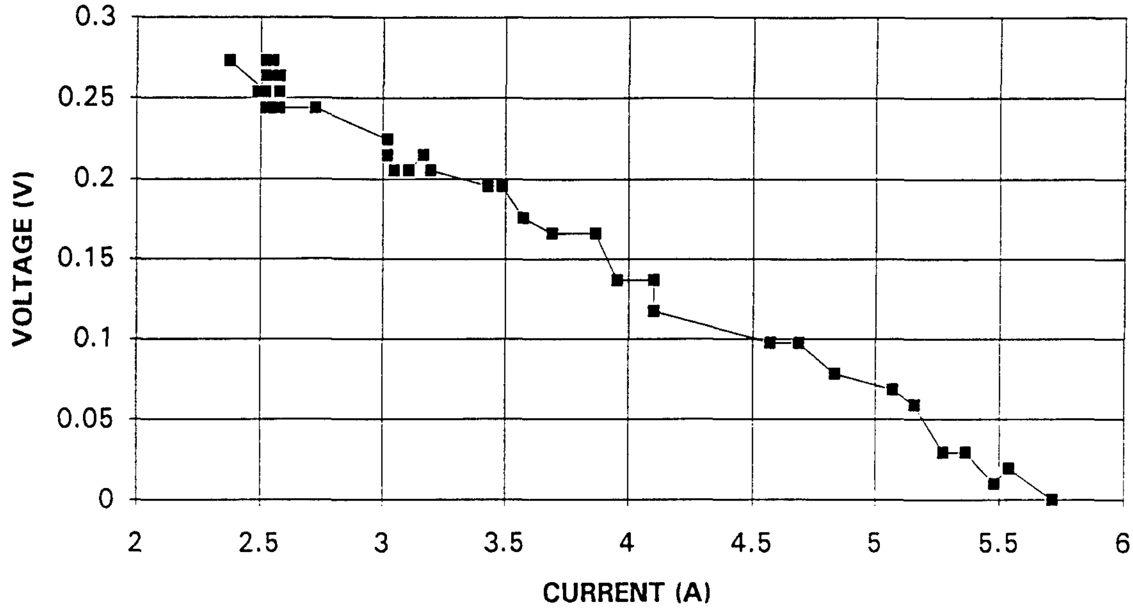

Figure 21. I-V Curve for Series Configuration of Protocells.

The series connection of three cells did not produce results that were as good as any one of the individual cells. However, the PL has determined that line losses and losses attributable to electrical connections caused the inferior performance of the cells in series. Further tests were discontinued based on the degradation of the even numbered cells and receipt of higher performance cells.

4.2.1 PROTOSYSTEM CONCLUSIONS

The possibility of operating all six cells together was eliminated due to the failure of three cell during the early characterization tests. However, operating three of the cell together was instructive in that PL and ORION were able to observe the importance of system influences such as wire length and internal cell impedance when a system of AMTEC devices is finally constructed. The high internal impedance and high lead resistance of the cells created load characteristics which resulted in poor performance of the three cells. This information was used in the development of the next phase of AMTEC cells which are to be tested at PL.

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